SEIR: A Stackelberg Game Based Approach for Energy-Aware and Incentivized Routing in Selfish Opportunistic Networks

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***Abstract*— Opportunistic Networks (OppNets) are a sub-class of wireless Delay Tolerant Networks (DTNs) that can be utilized in areas of sporadic network connectivity. OppNets consist of a network of mobile devices that cooperate with each other to forward messages from the source to the destination. However, in a practical real-world setting, nodes behave selfishly and do not choose to be cooperative all throughout. This selfish behavior could be exhibited due to a variety of reasons, ranging from lower energy levels of the node to memory or buffer shortages. Thus, it is imperative to develop incentivizing mechanisms that reward nodes that are cooperative and penalize nodes that are selfish. In this paper, we present a novel routing protocol called SEIR that is able to reduce energy consumption of nodes as well as incentivize them to participate in message routing. SEIR is based on the Stackelberg game theoretic model and decides the optimal reward to give relay nodes to eliminate their selfishness and improve chances of successful message delivery. Subsequent simulations performed show that SEIR outperforms existing routing protocols in terms of energy efficiency and message delivery in an OppNet with selfish nodes.**

Keywords*— *Opportunistic Networks; Energy-Aware Routing; Game Theory; Stackelberg Game; Incentive Mechanism

I. INTRODUCTION

OppNets are mobile networks that utilize the store-carry-forward paradigm. Nodes comprise of mobile devices that have the ability to store messages received and carry them for a fixed duration of time till they can be forwarded to the destination. Thus, OppNets house the potential to enhance communication in areas of scant network infrastructure, as nodes do not need to be constantly connected to each other for successful routing. Applications range from music concerts and conference gatherings to supervision of animals in wildlife sanctuaries and communication networks in rural areas.

It is important to note that routing in OppNets is a complex task as connections between nodes are intermittent and not continuous. Moreover, message forwarding in an OppNet is based on the assumption that relays will cooperate with each other to achieve this goal. Despite these challenges, a routing algorithm should aim to maximize message delivery probability as well as reduce the network overhead and the average latency or the average time taken to transmit messages from source to destination.

The basis for most work on OppNets assumes that nodes are intrinsically unselfish and would aid in message routing at all times. However, in a practical scenario, this assumption is unfounded as nodes display selfish behavior due to a multitude of factors. Most of these reasons are related to the issue of limited resources available for nodes, such as battery, bandwidth and buffer size. Also, it is essential to understand that whenever a node acts as a relay its battery levels as well as storage space will decrease. Hence, as the process of forwarding messages entails a cost with it, selfish nodes will seek to avoid incurring this cost and will not participate in message routing. It is evident that for a real world application of an OppNet, routing protocols should be devised that not only increase node participation in message forwarding but also help decrease energy consumption of nodes. This goal can be achieved by opting for mechanisms that reward active participation of nodes in the forwarding of messages and penalize them otherwise. Mechanisms can also be designed to limit interaction with detected selfish nodes so that they start participating in message forwarding if they want their messages relayed.

Game theory has seen diverse applications in a lot of different fields and seeks to mathematically model situations where players with different objectives compete for finite reserves. Game theory, and in particular the Stackelberg game model, has seen applications in economics and in the analysis of duopolies. The Stackelberg model was initially described as a non-cooperative competition between two firms – a leader and a follower. In this paper, this aspect of the Stackelberg game is employed to model the interaction of the source and the best possible relay as the source and the follower, respectively. Moreover, the Stackelberg equilibrium is then

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derived to meet the goals that are central to the successful functioning of the OppNet.

The rest of the paper is structured as follows – Section II describes related work in the domain of routing for selfish OppNets as well as energy efficient routing protocols. Section III and IV detail the proposed *SEIR* protocol and its mathematical formulation. Section V presents the simulation performed and the results obtained. Section VI lists the conclusion.

II. Related Work

Most research in the area of selfish node behavior in OppNets has largely culminated in various methods of incentivizing nodes to participate in message transmission by rewarding them. In a similar vein, nodes that behave selfishly can be punished. One such mechanism called *IRONMAN* was given by Bigwood et al. in [1]. *IRONMAN* first seeks to detect selfish nodes and then acts on them by punishing them for being selfish. The detection is carried out by using information housed by all the nodes in the network. Nodes store a *trust* value for each node that they come in contact with based on their past experience of whether or not their message was relayed by the other node. Thus, the *trust* value of a particular node decreases every time it acts selfishly. Eventually, if the *trust* value falls below a threshold, other relay nodes stop interacting with the selfish node. In this way, message delivery improves and the selfish character of nodes is kept to a minimum.

In [2] Buttyán et al. introduced a *barter trade* mechanism that was based on game theory. A node on coming in contact with another node would be provided with a list of messages that the other node was carrying. As such, if a message piqued the interest of the node, it could download the particular message and agree to forward it if the other node also agreed to take a message from its list. In this way, nodes would agree to work as long as their work was also being done.

Kangasharju et al. in [3] introduced a method based on purchasing power of nodes to combat selfishness. Nodes that partake in routing are given electronic coupons or credits. These credits can then be utilized by the nodes at access points in certain areas. This incentivizes nodes to participate in the routing process willingly.

Another efficient mechanism was given by Anantvalee et al. in [4] which has also been come to known as the *watchdog* mechanism. Here, each node is scrutinized by its neighbor nodes to see if it is forwarding messages or not. These nodes which host the *watchdog* node either increment or decrement the *reputation* of the node based on how selfishly it has been behaving. However, the *watchdog* mechanism assumes that selfish nodes will always be observed by neighbor nodes and fails to consider cases where this might not be true.

Many other trust based incentivizing schemes have been provided in literature. In [5] Goncalves et al. propose a scheme wherein node reputations are computed and are then labeled as "trustworthy", "no opinion", "very untrustworthy" or "untrustworthy". Trifunovic et al. devised the social trust approach in [6] and then categorized them as explicit or implicit. This was based on the concept of social trust and thus, explicit trust depicts social connections that a node shares with other nodes and implicit trust is a measure of the trustworthiness or honesty of a node. *COTTON* was given in [7] by Tamez et al. and classifies nodes into various divisions. Trust or reputation values are assigned to nodes by evaluating their behavior and also the group to which they belong. Some of the categories used are "private known helpers", "public unknown helpers", "trusted unknown helpers" and the like.

Selfish node detection in an OppNet can also play a vital role in mitigating their influence. After successful detection of selfish nodes, appropriate steps can be taken either to incentivize them to participate or to exclude them from the routing process. Many such detection mechanisms have been proposed in current research work. In [8] Ciobanu et al. proposed a collaborative mechanism in which nodes would collect information about other nodes by *gossiping*. Also, the authors use fuzzy values for the *altruistic* or *trustworthy* character of the node and ensure that these values are not binary. This helps add more depth to the character of the node and better quantify selfishness.

Game theory has also been used extensively in routing and security of a number of wireless networks ranging from *DTNs* to Cognitive Radio Networks. In particular the Stackelberg game theoretic model [9] has been employed in a number of different fields – from economics [10], the problem of flight scheduling [11] to airport security [12]. Moreover, the Stackelberg model has been very recently applied in the relaying of messages in *DTNs* by Rahmouni et al in [13]. The authors present a hierarchal Stackelberg game for message relaying. Their model employs efficient message caching by nodes and encourages nodes to accept messages and deliver them in fixed periods of time and without delay.

III. Proposed SEIR Protocol

A. Assumptions

Before detailing the proposed protocol, a few assumptions are made regarding the behavior of nodes and the OppNet in general. These are as follows –

- The OppNet is populated with nodes that are characteristically selfish.
- Selfish nodes can be made to participate in message relaying by giving them a reward for participation. The value of reward varies from zero to a given maximum value.
- Nodes can become unselfish even if the reward given to them is not the maximum possible value.
- Nodes that consume less energy are given higher reward to make the protocol energy efficient.

Thus the problem that arises is of choosing a suitable minimum reward for relay nodes such that nodes start participating in message forwarding and the energy consumed is also the minimum. For this, we model the interactions as a Stackelberg game.

B. Definitions

- *Time of Arrival* (τ_R): The Time of Arrival is defined

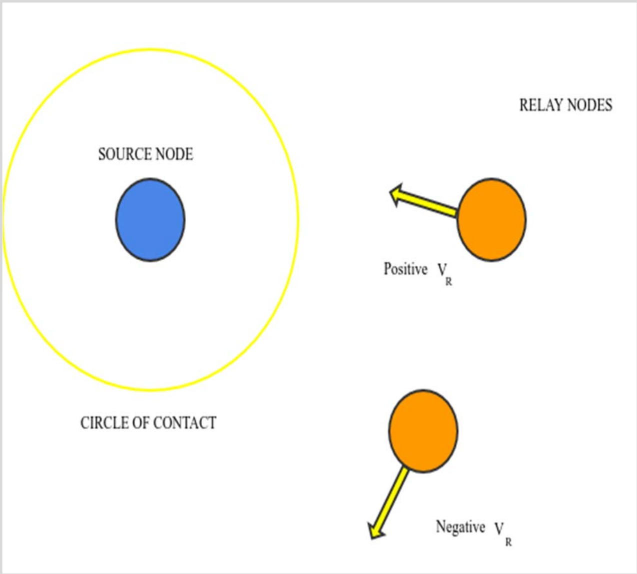

Fig. 1. Interaction between Source and Relay Nodes

as time that relay nodes will take to arrive within contact range of the source node in meters/sec. Moreover, it can be understood as the time taken to reach any point on the circumference of the source node's circle of contact range. Mathematically, it is the ratio of the Euclidean distance of the relay node from the source (D_R) and the velocity of the relay node (V_R). Here, V_R is in fact the relative velocity of the relay node with respect to the source node. However, since we assume the source to be at rest, V_R is basically the velocity of the relay node in question. V_R is taken to be a positive quantity if the relay node is moving towards the source node's circular area of contact and there is a possibility of it coming in contact with the source. V_R is taken to be a negative quantity if the relay node is moving away. Mathematically,

$$\tau_R = \frac{D_R}{V_R} \tag{1}$$

- *Energy Consumed (E_R)***:** The energy consumed by the node in the interacting with the source and aiding in message forwarding is labeled as E_R.
- *Energy Gain (G_R):* The gain in energy obtained is the mathematical reciprocal of the energy consumed.

$$G_R = \frac{k}{E_R} \tag{2}$$

where k is some constant value.

- *Reward (R_R):* The reward given to incentivize selfish nodes to participate in message relaying is labeled as R_R. It varies from 0 to R_{max}. That is, $R_R \in [0, R_{max}]$.

C. The Stackelberg Game Model

The Stackelberg game in this paper models the source node as the leader and the relay node as the follower. Higher reward is given to nodes that consume lesser energy. This relationship is modeled as –

$$R_R = \frac{e^{\frac{k}{E_R}} - \beta}{\alpha} \tag{3}$$

which can be written as,

$$\frac{e^{G_R} - \beta}{\alpha} = R_R \tag{4}$$

Therefore, we get the relation as,

$$G_R = \ln(\alpha R_R + \beta) \tag{5}$$

where α and β are constants.

Thus, the energy gain has been directly linked to the reward value. The gain in energy can then be maximized to achieve maximum energy efficiency.

Utility functions U_S for the source and U_R for the relay are then written-

$$U_S(R_R) = aG_R - dR_R \tag{6}$$

$$U_R(d) = dR_R - bR_R \tag{7}$$

where a is the gain/unit in energy, d is the strategy opted for by the relay node and b is defined, for the purpose of the paper, as reward earned/unit.

For the optimum energy saving and lower value of reward given, we impose the following pricing policy on the utility functions –

$$\max_{R_R}(U_S) \Rightarrow ensuring\ R_R \in [0, R_{max}] \tag{8}$$

$$max_d(U_S) \Rightarrow ensuring\ d > 0 \tag{9}$$

D. The Stackelberg Equilibrium

For R_R^* and d^* strategies opted to achieve Stackelberg equilibrium, the following conditions need to be true with regards to the utility functions –

$$U_S(R_R^*, d^*) \geq U_S(R_R, d^*)\ \forall R_R \in [0, R_{max}] \tag{10}$$

$$U_R(R_R^*, d^*) \geq U_R(R_R^*, d)\ \forall d > 0 \tag{11}$$

Thus, to evaluate the optimal choice of R_R^* and d^* Stackelberg equilibrium strategies, first the first order and second order partial derivatives of the utility functions with respect to R_R and d are calculated. To analyze the policy for the source the derivatives with respect to R_R are used and to do the same for the relay the ones calculated with respect to d are used –

$$\frac{\partial U_S}{\partial R_R} = \frac{a}{R_R + \alpha/\beta} \tag{12}$$

$$\frac{\partial^2 U_S}{\partial R_R^2} = \frac{-a}{(R_R + \alpha/\beta)^2} \quad (13)$$

For the source node, we see that the second order partial derivate function obtained is always concave and as a result there will always exist a unique solution to equation (10). Thus, when we put equation (10) equal to zero, we obtain the value of R_R*. Therefore,

$$R_R^* = \frac{a}{d} - \frac{\beta}{\alpha} \quad (14)$$

Next, we find $\frac{\partial U_R}{\partial d}$ and then, set it to zero, to obtain d*-

$$\frac{\partial U_R}{\partial d} = \frac{a}{d} - \frac{\beta}{\alpha} - \frac{(d-b)a}{d^2} \quad (15)$$

$$d^* = \sqrt{\frac{\alpha(ab)}{\beta}} \quad (16)$$

IV. Working of SEIR And Subsequent Analysis

The working of the *SEIR* protocol is divided into the explanatory steps listed below. The Stackelberg game model intrinsic to the working of the following steps is detailed in the previous section.

Step 1. Only relays in the vicinity of the source node moving towards the source's contact area are considered for message relaying. That is, only nodes with positive τ_R are considered.

Step 2. Knowing that there are some *N* possible relay nodes now in consideration, the best possible node for message transmission is chosen by comparing τ_R values. The node with the highest value of τ_R is chosen. In case of similar values for multiple nodes, one node is randomly picked out of all these nodes.

Step 3. The Stackelberg equilibrium is computed for the source as the leader and the previously chosen node as the follower. An optimum minimum value of R_R required is obtained and the maximum possible energy is conserved as a result.

Step 4. Another interaction where a node wants to transfer its message is again modeled as a Stackelberg game starting from Step 1.

In this paper, we have used the LR-I (Linear Reward Inaction) algorithm to update the strategies for the source until we achieve Stackelberg equilibrium. The optimization problem can be computed by a decentralized stochastic learning algorithm as the probability distribution of strategies for the source (R_R) are known and can be updated using LR-I rule until convergence occurs.

V. Simulations and Results

The simulations are carried out on the Opportunistic Network Environment (ONE) simulator and the SEIR protocol is compared against the GAER protocol, given by Dhurandher et al. in [14]. GAER describes an energy efficient routing protocol that is based on the genetic evolutionary algorithm used in numerous applications.

The energy settings for the nodes are also shown in Table 1. *Scan Energy* refers to energy consumed in scanning for devices in proximity or device discovery. *Scan Response Energy* refers to the energy consumed in responding to a scanning response or device discovery response. *Transmit Energy* is the energy consumed in transmitting messages from the host node to another node and the *Base Energy* is the energy consumed when the node is in an idle state and is not performing any actions. The *Initial Energy* is the initial energy level of the node. With time, due to all the other energy consumptions, the node's energy level keeps decreasing from its initial value of energy. All the energy consumptions, such as required in scanning and scan response, are considered in total to amount to the value of E_R developed in previous sections.

It is seen that *SEIR* outperforms *GAER* in terms of average residual energy of nodes and number of messages delivered in an OppNet environment with selfish nodes with respect to number of nodes and speed of nodes. The average residual energy of nodes is defined as the energy remaining in nodes after the simulation is complete. The number of messages delivered characteristic is the number of messages successfully delivered from source node to destination node. The values of $\alpha, \beta, a, b, R_{max}$ in the simulation are chosen as 1.5, 1, 1.66, 0.33, 100 respectively. In the *GAER* protocol used here, all possible relay nodes are given $R_{max}/2$ as reward so they may or may not aid in message routing.

TABLE 1. Simulation Parameters' Initializations.

Parameter	Value
Simulation Area	4.5km x 3.4km
Comm. Interface	Bluetooth
Transmission Range	12m
Transmission Speed	2.5 Mbps
Buffer Size	5 Mb
Size of Message	500kb – 1Mb
Simulation Time	43200 s
Message TTL	300 min
Message Generation	25 – 35 s
Node's Speed Range	0.5 – 2.5 m/s
Reward value range	0 – 100
α	1.5
β	1
a	1.66
b	0.33
Initial Energy	5000 U
Scan Energy	0.1 U
Transmit Energy	0.2 U
Base Energy	0.01 U
Scan Response Energy	0.1 U

It is seen that in terms of average residual energy and messages delivered, *SEIR* does much better than *GAER*. Moreover, it is evident from Fig 3 and Fig 5 that whenever the speed of nodes is increased, *SEIR* starts performing even better. This happens because with an increase in V_R, the arrival time of nodes increases. As more nodes are in competition to be chosen as best relay the network is constantly being used for routing. It is in fact, even seen through Fig 2 and Fig 4 that with an increase in number of nodes, *SEIR* gets better at routing, solely because more nodes would want to relay messages once their ideal reward is given to them.

GAER is unable to perform well under all circumstances because it essentially becomes a game of hit and trial, and it is uncertain whether or not a node would participate in message forwarding or not. It is seen through results obtained that *SEIR* is supremely energy efficient and is also good at incentivizing selfish nodes.

Overall, in the *SEIR* protocol, nodes exhibit higher energy reserves at the end of the simulation as can be seen in Fig 2. As *SEIR* is able to derive payoffs which maximize the energy conserved by the relay nodes, higher energy levels are observed. In *GAER,* if selfishness is prevalent throughout the network it should lead to higher energy levels as *Base Energy* is a very small value. However, since it can be seen in Fig. 2 that this is not the case, it is likely that nodes, which participate in routing, cannot keep a check on their energy expenditure. As a result, average residual energy after the simulation ends, is low. Fig. 3 illustrates a similar trend when the varying parameter is the speed of the nodes.

It is also worthwhile to note that in *SEIR,* the number of messages delivered are always much higher than the numbers ensured by *GAER*. Much of this can be attributed to the fact that the Stackelberg equilibrium computed is encouraging more and more relay nodes to participate in routing. As the participation increases, the delivery probability also increases. This trend is evident from Fig. 4 and Fig. 5.

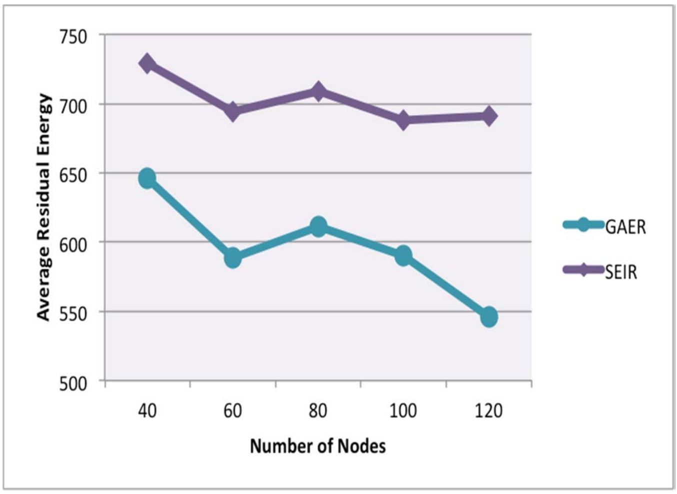

Fig. 2

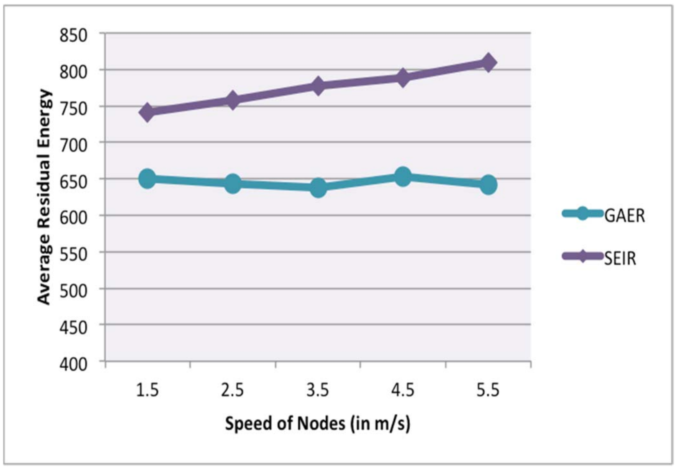

Fig. 3

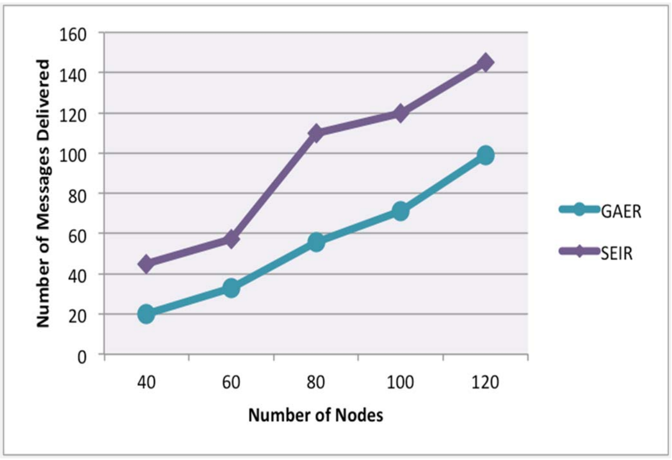

Fig. 4

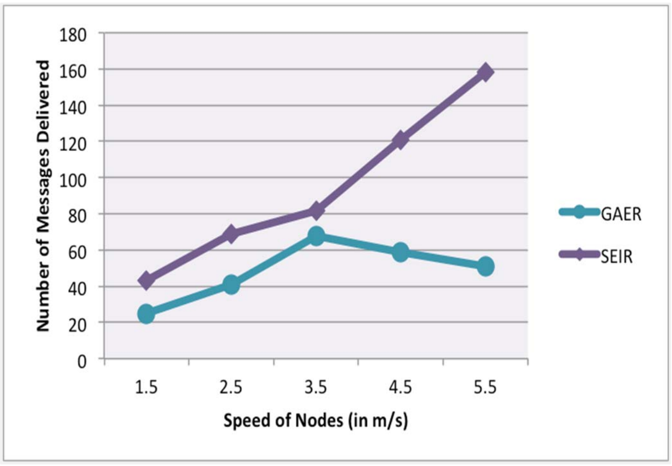

Fig. 5

VI. Conclusion

In this paper, we have presented a novel routing protocol in OppNets with selfish nodes. This protocol, as is seen through observations and results, is robust at saving energy of nodes and is also efficient at increasing the probability of successful message delivery. This mechanism is based on the concept of Stackelberg game theory models. Ideal amounts of rewards to be given to selfish nodes are computed using the Stackelberg equilibrium that has been so derived. Mathematical calculations and derivations are in lieu with the results obtained. The *SEIR* protocol also outperforms *GAER,* an existing energy-aware routing mechanism.

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